Scientia Horticulturae 252 (2019) 238–242

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Adaptability and stability of *Coffea canephora* genotypes cultivated at high altitude and subjected to low temperature during the winter

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ARTICLE INFO

Keywords:
Cultivar
Breeding
Productivity
Low temperature

ABSTRACT

Climate change prospections indicate large fluctuations in terrestrial temperature, what may change the zoning of coffee cultivation. This is particularly true for *Coffea canephora* (conilon or robusta coffee) to which some suitable areas may become inappropriate. Thus, conilon cultivation at high altitudes may be an option to establish *C. canephora*, mitigating the possible effects of productive areas loss. In this context, the aim of this work was to evaluate the productivity, adaptability and stability of 28 *C. canephora* genotypes cultivated at 850 m above sea level, under climatic conditions where the minimum temperature is the limiting factor for the species. A random block design with four replicates x five plants per replicate was used. The genotype x environment interaction was investigated using stability and adaptability analyzes based on the mixed model of restricted maximum likelihood / best linear unbiased prediction (REML/BLUP). The genotypes presented heritability of high magnitude, indicating the precision of selection. Six genotypes (NV2, NV8, P1, 3V, Verdim TA and A1) were highlighted for productivity, adaptability and stability at high-altitude and low temperature.

1. Introduction

The species *Coffea canephora*, also known as conilon or robusta coffee, is currently cultivated at low to medium elevations in the intertropical regions of Africa, America and Asia, adapting well to warmer climates without large variations in temperature and with precipitation above 1200 mm per year (Montagnon et al., 2012; Cubry et al., 2013; Barbosa et al., 2014). *C. canephora* presents a higher growth rate when cultivated in climates with minimum air temperatures above 17 °C (Partelli et al., 2010, 2013) and mean maximum air temperature below 33 °C (Covre et al., 2016; Dubberstein et al., 2017). Therefore, *C. canephora* cultivation at high-altitudes may present developmental problems, mainly during the coldest months of winter.

With the advent of climatic changes in recent years, namely the increase in temperature and prolonged droughts (IPCC, 2015), strong losses of areas suitable for coffee cultivation in important producing countries like Brazil and Vietnam have been reported (Bunn et al., 2015).

Under this scenario, the analysis of the genotype x environment interaction (G x E) should be the first step to evaluate the real impact and to ensure a high degree of reliability for the genotypes' selection, maximizing productivity and other agronomic attributes of interest for a given location or group of environments (Rosado et al., 2012; Santos et al., 2016) Considering that *C. canephora* presents high genetic variability (Giles et al., 2018, 2019) due to the species allogamy, it is possible that some genotypes may be capable of exploring different physiological mechanisms as a strategy to tolerate low temperatures and recovery after stress (Partelli et al., 2009, 2011; Batista-Santos

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https://doi.org/10.1016/j.scienta.2019.03.044
Received 28 July 2018; Received in revised form 23 February 2019; Accepted 22 March 2019
Available online 03 April 2019
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et al., 2011; Ramalho et al., 2018), as well as environments with high temperatures (Martins et al., 2016, 2017; Rodrigues et al., 2016).

Thus, based on the knowledge regarding plant mechanisms and the great genetic variability of *C. canephora*, and through a breeding program that aims at obtaining cultivars adapted to the climatic conditions of high altitudes, it is possible to search for genotypes and / or cultivars tolerant to these conditions. Hence, it is consistent to evaluate *C. canephora* genotypes at high altitude sites. Therefore, the objective of this work was to evaluate the productivity, adaptability and stability of 28 *C. canephora* genotypes cultivated at climatic conditions of high altitude, with stress evidenced by low temperatures in the winter and high temperatures in the summer.

2. Material and methods

The experiment was carried out at in the municipality of Morrinhos, state of Goiás, in Brazil, located at an altitude of approximately 850 m. The region of Morrinhos is characterized by water deficit from April to October, presents flat topography and undulating relief, average annual temperature of 20 °C, with the minimum air temperature ranging from 10 °C to 20 °C, presenting some days with temperature below 8 °C.

To implement the crop, 28 *C. canephora* genotypes (Table 1) were selected, 25 of which were propagated by cuttings and three propagated by seeds. *C. canephora* seedlings used in the planting were produced in certified nursery. The spacing used for planting was 3.5 m x 1.0 m, occupying 3.5 m^2 per plant.

For the experiment, we used a random block design, with four repetitions, each of which composed by five plants. The cultural treatments, corresponding to fertilization, were carried out according to the technical guidelines for the coffee crop (Fonseca et al., 2015). Pruning was carried out to control branches in excess, maintaining a standard of *ca*. 12,000–15,000 stems/ha (equivalent to 3–4 stems per plant). In each of the four experimental years, manual weeding, mechanized weeding and chemical weeding were performed. No micronutrients, insecticides or fungicides were applied during the four years of the study. The experimental area was irrigated during the entire cropping season, but in the harvests of 2015 and 2016 no irrigation was applied. To analyze the stability and adaptability of the genetic material evaluated in this study, yield data corresponding to four crop seasons (2013, 2014, 2015, 2016) were used.

To investigate the genotype x environment interaction, stability and adaptability analyzes were combined using the mixed model restricted maximum likelihood / best linear unbiased prediction (REML/BLUP). This method has been successfully used, especially in perennial crops (Maia et al., 2009; Rosado et al., 2012; Rodrigues et al., 2017). The individual BLUP is suitable for predicting genetic values basically composed by a random statistical model effect associated with phenotypic observations, adjusting the data for the fixed effects and the uneven amount of information upon the parcels when appropriate.

The genetic parameter estimates were obtained through analysis involving the REML/BLUP procedure, using the statistical model 55 of the Selegen software (Resende, 2007). Data from four crop seasons were considered for the adaptability and stability estimates of the different *C. canephora* genotypes. The selection of superior genotypes was based on the harmonic mean of the relative performance of genetic values (HMRPGV), using 3 strategies: selection based on the predicted genetic value, considering the average performance in all crops (without interaction effect); selection based on the predicted genetic value, considering the performance of the genotypes in each crop season (with interaction effect); and simultaneous selection for production, stability (HMGV) and adaptability (RPGV).

Table 1
List of 28 accessions of *C. canephora* genotypes used in the experiment, in Morrinhos, Goiás, Brazil.

A	AC	A	AC
1 V	1	NV2	14
2 V	2	14 from Emcapa 8121	15
3 V	3	Clone 18	16
4V	4	NV1	17
5V	5	NV8	18
6V	6	P1	19
7V	7	3 from Emcapa 8121	20
8V	8	P2	21
9V	9	4 from Bahia	22
10V	10	NV3	23
11 V	11	Verdim TA	24
12 V	12	A1	25
13 V	13	Robustão Seeds	26, 27 and 28

(**A**): Accessions; (**AC**): Accessions code, regarding 28 *C. canephora* genotypes analyzed in the experiment. 1 V and 2 V are genotypes that comprise the Vitória cultivar. A1 comprises the *Tributun* cultivar. 3 and 14 from Emcapa comprise Emcapa 8121 cultivar. AC 14,18,19,24,and 25 from Andina cultivar.

3. Results and discussion

Based on the average productivity, the genotypes 03, 14, 18, 19, 24 and 25 were highlighted (Table 2) with yields quite superior to the national average and without pest and disease control.

In plant breeding programs, the experiments planning, and conduction stages can be based on the interpretation of the genetic parameters estimates, which allows to infer the experimental quality, the proportion of total variance that is due to genetic differences and finally identifies the gain prediction with the selected clones planting (Ramalho et al., 2016).

High values for genetic variance (V_g) were in general observed, with the highest value (549.49) observed in 2015 (Table 3). It is noteworthy that there was a predominance of genotypic variations regarding the environmental variations, in terms of the processed coffee expression, when evaluated together or by year (Table 3). High estimates of

Table 2
Average of four repetitions in each year of evaluation of the productivity of 28 *C. canephora* genotypes cultivated at high altitude in Morrinhos, Goiás, Brazil.

Genotypes	Productivity in sc ha^{-1}				
	2013	2014	2015	2016	Average
1	8.0	23.5	18.4	0.2	12.5
2	0.0	11.0	14.5	10.0	8.9
3	29.0	39.2	56.1	32.9	39.3
4	2.0	30.5	28.1	1.0	15.4
5	7.7	25.8	41.4	1.9	19.2
6	10.5	28.1	10.5	4.2	13.3
7	9.2	25.1	3.4	0.3	9.5
8	14.7	39.3	37.2	0.4	22.9
9	0.0	18.7	39.2	1.8	14.9
10	12.5	34.3	34.2	1.7	20.7
11	16.0	33.6	39.0	5.1	23.4
12	11.6	46.8	17.1	1.5	19.2
13	4.9	53.7	39.6	13.2	27.8
14	45.0	54.7	100.9	39.0	59.9
15	0.0	0.0	0.0	0.0	0.0
16	3.5	25.5	0.0	0.6	7.4
17	5.8	34.7	44.6	8.3	23.3
18	22.8	66.0	77.8	26.1	48.2
19	10.5	78.2	40.3	17.8	36.7
20	9.5	33.9	15.5	0.0	14.7
21	6.8	13.5	57.2	28.5	26.5
22	7.0	30.3	67.6	1.2	26.5
23	16.2	38.5	23.3	4.3	20.6
24	13.8	43.6	99.1	50.6	51.8
25	50.4	83.3	61.2	39.1	58.5
26	2.4	26.2	36.8	16.0	20.3
27	2.7	23.0	35.3	1.8	15.7
28	3.2	12.4	22.9	2.2	10.2

Table 3
Estimates of genetic parameters for productivity (sacks of 60 kg ha^{-1}) of processed coffee grains, obtained from the evaluation of 28 *C. canephora* genotypes cultivated at high altitude in four years, in Morrinhos - Goiás, Brazil.

Genetic parameters	Year				Joint
	2013	2014	2015	2016	
Vg	134.1	273.44	549.49	176.89	170.95
Vp	–	–	–	–	17.15
Vgm	–	–	–	–	115.55
Ve	46.99	226.31	185.27	95.39	124.28
Vf	181.1	499.75	734.76	272.28	427.93
(h^2_{mc})	0.92	0.83	0.92	0.88	0.81
r	–	–	–	–	0.44
c^2perm	–	–	–	–	0.04
c^2gm	–	–	–	–	0.27
r_{gcrop}	–	–	–	–	0.60
Average accuracy	0.93	0.88	0.93	0.90	0.87
CVg (%)	90.55	46.04	57.87	112.95	52.56
CVe (%)	53.6	41.88	33.6	82.94	44.81
CVr	1.69	1.10	1.72	1.36	1.17

V_g: Genetic variance between genotypes; V_p: Environmental variance between parcels; V_{gm}: Variance of the genotypes x crops interaction; V_e: Residual variance between parcels; V_f: Individual phenotypic variance; Individual heritability of restrict sense, in the block (h^2_{mc}); r: Coefficient of individual repeatability. c^2perm: Coefficient of determination of the parcel effects; c^2gm: Coefficient of determination of the effects of the genotypes x crops interaction; r_{gcrop}: Genetic correlation throughout crops; CV_g (%): Coefficient of genetic variation; CV_e (%): Coefficient of environmental variation; CV_r: Ratio between coefficient of genetic variation / coefficient of environmental variation.

genotypic variance in *C. canephora* were also reported by other authors (Ramalho et al., 2016; Oliveira et al. 2018). Estimates of low magnitude were also observed in studies involving different genotypes of *Coffea* spp. cultivated under different soil and climatic conditions (Rodrigues et al., 2013).

The average heritability parameter of the clones (h^2_{mc}) was considerably high, ranging from 0.83 (2014) to 0.92 (2013 and 2015) (Table 3). The values observed for the parameter h^2_{mc} are similar to those found by Ramalho et al. (2016) who observed an average of 0.94 for h^2_{mc}, in a study involving genetic parameters of the coffee yield, evaluated in four crop seasons to select 'conilon' coffee clones, in the experimental field of Ouro Preto do Oeste (RO).

According to the joint analysis of the data, the variances attributed to the genotypes were higher when compared to the variances occurred for environments (V_p) and genotype x environment interaction (V_{gm}), with the value of V_p (17.15) lower than the value of V_{gm} (115.55) (Table 3). These results can be understood as we consider the results observed by Fehr (1987), where high heritability was associated with higher additive genetic variance, lower environmental variation and lower genotype x environment interaction.

For the mean accuracy of genotype selection, the values 0.93, 0.88, 0.93 and 0.90 were respectively observed for the 2013, 2014, 2015 and 2016 crop seasons. The highest value of 0.93 for mean accuracy of genotype selection was observed for the 2013 and 2015 crops, and the combined estimate of the four crops reveals an average accuracy value of 0.87. The fact that high values were obtained for the accuracy parameter is relevant considering that this parameter is intended to help in the correct ordering of the cultivars, for selection purposes, and in the inference efficacy related to the genotype value of the cultivar, due to the fact that it does not only depend on the magnitude of the residual variation and the number of repetitions, but also on the ratio between the genetic and residual variations associated to the character under evaluation (Resende, 2002; Resende and Duarte, 2007).

The correlation between true genotypic values and estimated ones, interpreted by the accuracy of the selection procedure, quantifies the inference effectiveness of the genotypic value of each clone as a function of the number of measurements (crop seasons) evaluated (Cecon et al., 2008; Rocha et al., 2009). According to Resende (2002), the value of the accuracy of selection among the clones (0.86) showed a precision in the genotypic values inferences, indicating that the experimental conduction was appropriate and the evaluations of the four harvests sufficient for the characterization of the superior genotypes.

The values of the coefficients of genetic variation were always higher when compared to the coefficients of environmental variation independent of the evaluated crop. Consequently, for all four crop seasons evaluated in the study, the results of the genetic variation / environmental variation (CV_r), always presented values above one, with the highest value of 1.72 obtained in 2015. The CV_r values varied significantly among the seasons evaluated, which can be explained by the difference between the productivity over the years (Table 3).

The knowledge regarding the coefficient of repeatability of the characteristics of interest allows to evaluate the expenditure of time necessary for the selection of genetically superior individuals to be made with the accuracy desired by the researcher (Bruna et al., 2012). The coefficients of joint individual repeatability obtained in this study involving the yield analysis of processed coffee beans in four crop seasons presented the value of 44% (Table 3). According to the classification of Resende (2002), the value of 45% of joint repeatability represents an average magnitude. Therefore, in order to increase the experimental accuracy, a greater number of measurements per plant should have been used (Resende, 2002).

The value of 0.60 of the genetic correlation through the crops (r_{gcrop}), reveals moderate level of complex interaction (Table 3). This behavior indicates that there are differences in genotype classifications considering the different seasons, i.e. a particular genotype that is ranked as first in t2013, will not necessarily be the genotype classified as first in the following years.

Table 4 shows the average genotypic values ($\hat{\mu} + \tilde{g}$) for each of the four crop seasons evaluated in the study. The six best genotypes that can be considered differentiated and selected according to BLUP were: 3 V, NV2, NV8, P1, Verdim TA and A1 (accessions 3, 14, 18, 19, 24 and 25, respectively). Based on the results, it is possible to cultivate these six genotypes in different environments from the place where this experiment was established, because the genotypes were ordered based on genotypic values free from the genotype x environment interaction.

According to Conab (2017), in 2016, Brazil presented an average yield of 18.81 sacks ha^{-1}. Seventeen of the 28 *C. canephora* genotypes analyzed in the study present a much higher average productivity when compared to the Brazilian productivity average. Thus, it can be indicated that there are genetic resources of this species that can adapt to altitude and low temperatures. These genetic resources may be important to implement the expressiveness of *C. canephora* production.

Table 5 shows the differentiated pattern between the estimates of the genotypic values for the average environment, with the average interaction (u + g + gem) capitalized by the HMRPGV method, which shows superiority for six genotypes: 3 V, NV2, NV8, P1, Verdim TA and A1 (accessions 3, 14, 18, 19, 24 and 25, respectively) since these are always presented among the first six settings.

The results presented in Tables 4 and 5 indicate different values when compared to each other. However, a similarity was observed in the indication of the best genetic materials. For the six genotypes considered superior, higher values for estimates of genetic parameters involving the genotype x environment interaction were observed when compared to the values of the genetic parameter estimates that do not involve the genotype x environment interaction.

Thus, we may consider that the values for estimates obtained by the genotype x environment interaction will especially be applicable if the clones are planted in areas with the same genotype x environment interaction pattern of the experimental network of this evaluation. Thus, the inferences about genotypic averages based on estimates obtained without the use of genotype x environment interaction will be safer to be used as reference (Bastos et al., 2007).

The results of the present work, along with additional information,

Table 4
Estimates of the genetic values related to the productivity character (sacks of 60 kg ha^{-1}) of processed coffee beans, not considering the genotype x environment interaction, obtained from the evaluation of 28 *C. canephora* genotypes cultivated at high altitude, in four crops, in the municipality of Morrinhos - Goiás.

Clones	Crops				VG (Average)	Accuracy
	2013 $\hat{\mu}_1 + \tilde{g} + \tilde{g}s$	2014 $\hat{\mu}_2 + \tilde{g} + \tilde{g}s$	2015 $\hat{\mu}_3 + \tilde{g} + \tilde{g}s$	2016 $\hat{\mu}_4 + \tilde{g} + \tilde{g}s$	$\hat{\mu} + \tilde{g}$	
14	43.41	55.84	93.45	37.85	52.90	0.88
25	45.35	78.56	64.44	39.39	52.30	0.87
24	17.66	47.58	87.31	45.18	45.88	0.87
18	25.76	61.31	70.81	26.33	42.99	0.88
3	26.42	40.56	53.43	28.68	35.48	0.88
19	12.54	70.98	42.06	16.84	34.05	0.88
13	6.83	50.43	40.25	13.25	27.28	0.88
22	9.10	30.66	59.39	5.38	25.95	0.87
21	6.97	17.91	53.67	22.33	25.17	0.88
17	6.94	36.22	43.55	8.79	24.02	0.88
11	14.92	33.89	39.07	6.16	23.71	0.88
8	12.60	38.24	37.48	2.59	23.04	0.88
23	14.62	37.29	26.56	5.11	21.47	0.88
10	10.34	33.91	34.74	2.99	21.13	0.88
26	3.84	27.42	36.70	10.22	20.31	0.88
12	10.74	43.62	21.09	2.42	20.25	0.87
5	4.81	26.95	37.91	4.50	19.46	0.87
9	–	22.26	38.12	2.53	18.16	0.85
20	8.67	32.20	21.59	–	17.88	0.85
16	3.90	26.08	–	2.49	17.60	0.85
27	3.24	23.38	36.02	2.51	17.53	0.87
4	2.53	28.59	28.22	1.60	16.63	0.88
6	9.03	27.97	15.31	3.95	15.63	0.88
1	6.97	24.30	21.21	1.76	15.20	0.88
7	7.53	25.10	11.13	0.40	13.04	0.88
28	2.72	15.07	24.24	1.10	12.82	0.88
2	–	15.41	16.86	7.16	11.77	0.85
General average	11.91	35.99	40.28	11.33	24.88	–
Genetic gain (%)	88.16	45.71	51.02	119.69	47.14	–

Note: Genotype 15 died due to the low temperatures.

Table 5
Genotype values capitalizing the genotype x mean environment interaction (u + g + gem), stability of genotypic values (HMGV), adaptability of genotypic values (RPGV) and stability and adaptability of genotypic values (HMRPGV) for the characteristic productivity of coffee grains, from the evaluation of 28 *C. canephora* genotypes cultivated at high altitude, in four crops, in the municipality of Morrinhos, Goiás, Brasil.

Clones	u + g + gem	Clones	HMGV	Clones	RPGV *GA	Clones	HMRPGV *GA
14	57.6377	25	52.8514	25	68.8408	25	60.922
25	56.9359	14	51.238	14	67.5316	14	60.3389
24	49.4337	18	37.3067	24	55.7317	18	48.5845
18	46.0564	24	35.9614	18	49.4437	24	46.4405
3	37.2704	3	34.4538	3	44.8015	3	40.01
19	35.6047	19	22.6007	19	34.5551	19	32.2354
13	27.6914	20	15.5681	21	27.2798	13	23.08
22	26.1338	21	15.2204	13	25.7738	11	21.0425
21	25.219	13	15.0119	11	23.0647	17	20.2172
17	23.8748	11	14.0663	22	22.1737	21	19.9949
11	23.5102	17	12.9727	17	21.4351	22	18.8928
8	22.7287	23	12.1706	23	20.9868	23	18.046
23	20.8954	22	11.5838	8	20.3985	20	17.1297
10	20.4982	2	11.3728	10	18.2707	26	15.0353
26	19.5433	26	9.4807	26	18.0188	10	13.9058
12	19.4666	6	8.609	20	17.9017	8	13.568
5	18.5448	10	8.1801	12	17.7309	5	13.4672
9	17.0263	5	8.1058	5	15.4955	6	12.2851
20	16.6965	8	7.7183	9	14.8284	2	11.8349
16	16.367	12	6.937	6	14.0876	12	11.6739
27	16.2878	9	6.4304	27	12.6738	9	10.4345
4	15.2338	27	5.1494	2	12.2654	27	9.1824
6	14.0679	1	5.0048	1	12.0818	1	8.6403
1	13.5604	16	4.3056	4	11.4959	16	8.3043
7	11.0414	4	3.6632	16	10.5452	4	6.869
28	10.7795	28	2.8836	7	10.2112	28	5.3049
2	9.5591	7	1.4493	28	8.3677	7	2.849

GA = General Average.

provided knowledge for the indication of more appropriate clones, promoting an advance in the registration of a new cultivar, even though that was not the objective of the work. Thus, six genotypes have compassed a cultivar registered in the Ministry of Agriculture, Livestock and Food Supply. This cultivar should be cultivated at low temperature (the first of Brazil or of the world) and it is named Andina.

4. Conclusions

Regarding the productivity of processed coffee, significant genetic variability was verified among the genotypes evaluated in the study, a condition that favors the obtention of gains with the clonal selection.

The genotypes heritability presented high magnitude, a result that increases the precision and consecutively the success in the selection of genotypes.

Among the evaluated genotypes, six genetic material, NV2, NV8, P1, 3 V, Verdim TA and A1, were highlighted in productivity, adaptability and stability.

There are *C. canephora* genotypes evaluated in the study that present the potential to be successfully used in breeding programs, aiming the cultivation of *C. canephora* at high altitude, under low temperature conditions.

Declarations of interest

None.

Acknowledgements

The authors thank the Universidade Federal do Espírito Santo (UFES) for the support to the investigation, the Federal Instituto Goiano from Morrinhos – Goiás for the availability of experimental resources, the Instituto Capixaba de Pesquisa, Assistencia Tecnica e Extensao Rural (Incaper) for providing seedlings from part of the accessions of *C. canephora* genotypes analyzed in the study, the Fundacao de Amparo a Pesquisa e Inovacao do Espirito Santo (Fapes) for financial support and the Conselho Nacional de Desenvolvimento Cientifico e Tecnologico (CNPq) for financing the establishment of the crops. All from Brazil. Portuguese national funds from Fundação para a Ciência e Tecnologia to the research units UID/AGR/04129/2013 (LEAF) and UID/GEO/04035/2013 (GeoBioTec) (J.C. Ramalho and A.I. Ribeiro-Barros) are also greatly acknowledged.

References

Barbosa, D.H.G.S., Rodrigues, W.P., Vieira, H.D., Partelli, F.L., Viana, A.P., 2014. Adaptability and stability of conilon coffee in areas of high altitude. Genet. Mol. Res. 13 (3), 7879–7888.

Bastos, I.T., Barbosa, M.H.P., Resende, M.D.V., Peternelli, L.A., Silveira, L.C.I., Donda, L.R., Fortunato, A.A., Costa, P.M.A., Figueiredo, I.C.R., 2007. Avaliação da interação genótipo x ambiente em cana-de-açúcar via modelos mistos. Pesquisa Agropecuária Tropical 37 (4), 195–203.

Batista-Santos, P., Lidon, F.C., Fortunato, A., Leitão, A.E., Lopes, E., Partelli, F.L., Ribeiro, A.I., Ramalho, J.C., 2011. The impact of cold on photosynthesis in genotypes of *Coffea* spp.- photosystem sensitivity, photoprotective mechanisms and gene expression. J. Plant Physiol. 168, 792–806.

Bruna, D.E., Moreto, A.L., Dalbó, M.A., 2012. Uso do coeficiente de repetibilidade na seleção de clones de pessegueiro para o litoral sul de Santa Catarina. Rev. Bras. Frutic. 34, 206–215. https://doi.org/10.1590/S0100-29452012000100028.

Bunn, C., Laderach, P., Rivera, O.O., Kirschke, D.A., 2015. Bitter cup: climate change profile of global production of Arabica and Robusta coffee. Clim. Change 129 (1–2), 89–101.

Cecon, P.R., Silva, F.F., Ferreira, A., Ferrão, R.G., Carneiro, A.P.S., Detmann, E., Faria, P.N., TSDS, Morais, 2008. Repeated measure analysis in the clonal evaluation in 'Conilon' coffee. Pesquisa Agropecuária Brasileira 43 (9), 1171–1176.

Conab, 2017. Acompanhamento da safra brasileira: Café: primeiro levantamento (Accessed 20 July 2017) Disponível em:. http://www.conab.gov.br/OlalaCMS/uploads/arquivos/17_01_17_14_51_54_boletim_cafe_-_janeiro_de_2017.pdf.

Covre, A.M., Partelli, F.L., Bonomo, R., Braun, H., Ronchi, C.P., 2016. Vegetative growth of Conilon coffee plants under two water conditions in the Atlantic region of Bahia State, Brazil. Acta Scientiarum. Agron. 38 (4), 535–545. https://doi.org/10.4025/actasciagron.v38i4.30627.

Cubry, P., Bellins, F., Pot, D., Musoli, P., Leroy, T., 2013. Global analysis of *Coffea canephora* Pierre ex Froehner (Rubiaceae) from the Guineo-Congolese region reveals impacts from climatic refuges and migration effects. Genet. Resour. Crop Evol. 60, 483–501.

Dubberstein, D., Partelli, F.L., Dias, J.R.M., Espindula, M.C., 2017. Influência da adubação no crescimento vegetativo de cafeeiros na Amazônia sul ocidental. Coffee Sci. 12 (2), 50–59.

Fehr, W.R., 1987. Principles of Cultivars Development. Macmillan, New York 536 p.

Fonseca, A., Sakiyma, N., Borém, A., 2015. Café Conilon do plantio à colheita, first ed. UFV, Viçosa, MG, pp. 257.

Giles, J.A.D., Partelli, F.L., Ferreira, A., Rodrigues, J.P., Olios, G., Silva, F.H.L., 2018. Genetic diversity of promising 'conilon' coffee clones based on morpho-agronomic variables. Ann. Braz. Acad. Sci. 90, 2437–2446.

Giles, J.A.D., Ferreira, A.D., Partelli, F.L., Aoyama, E.M., Ramalho, J.C., Ferreira, A., Falqueto, A.R., 2019. Divergence and genetic parameters between *Coffea* sp. genotypes based in foliar morpho-anatomical traits. Sci. Hortic. 245, 231–236.

IPCC, 2015. Working Group III. Mitigation of Climate Change. 99 p.. Intergovernmental panel on climate change (Accessed 20 July 2015). http://report.mitigation2014.org/drafts/final-draft-postplenary/ipcc_wg3_ar5_final-draft_postplenary_technical-summary.pdf.

Maia, M.C.C., Resende, M.D.V., Paiva, J.R., Cavalcanti, J.J.V., 2009. Seleção simultânea para produção, adaptabilidade e estabilidade genotípicas em clones de cajueiro, via modelos mistos. Pesquisa Agropecuária Tropical 39, 43–50.

Martins, M.Q., Rodrigues, W.P., Fortunato, A.S., Leitão, A.E., Rodrigues, A.P., Pais, I.P., Martins, L.D., Silva, M.J., Reboredo, F.H., Partelli, F.L., Campostrini, E., Tomaz, M.A., Scotti-Campos, P., Ribeiro-Barros, A.I., Lidon, F.J.C., Damatta, F.M., Ramalho, J.C., 2016. Protective response mechanisms to heat stress in interaction with high[CO_2] conditions in *Coffea* spp. Front. Plant Sci. 7https://doi.org/10.3389/fpls.2016.00947. art497.

Martins, M.Q., Fortunato, A.S., Rodrigues, W.P., Partelli, F.L., Campostrini, E., Lidon, F.C., Damatta, F.M., Ramalho, J.C., Ribeiro-Barros, A.I., 2017. Selection and validation of reference genes for accurate RT-qPCR data normalization in *Coffea* spp. under a climate changes context of interacting elevated [CO2] and temperature. Front. Plant Sci. 8https://doi.org/10.3389/fpls.2017.00307. art307.

Montagnon, C., Cubry, P., Leroy, T., 2012. Amélioration génétique du caféier *Coffea canephora* Pierre: connaissances acquises, stratégies et perspectives. Cah. Agric. 21 (2–3), 143–153.

Oliveira, L.N.L., Rocha, R.B., Ferreira, F.M., Spinelli, V.M., Ramalho, A.R., Teixeira, A.L., 2018. Selection of *Coffea canephora* parents from the botanical varieties Conilon and Robusta for the production of intervarietal hybrids. Ciência Rural 48 (4), 1–7. https://doi.org/10.1590/0103-8478cr20170444.

Partelli, F.L., Vieira, H.D., Viana, A.P., Batista-Santos, P., Rodrigues, A.P., Leitão, A.E., Ramalho, J.C., 2009. Low temperature impact on photosynthetic parameters of coffee genotypes. Pesquisa Agropecuária Brasileira 44 (11), 1404–1415.

Partelli, F.L., Vieira, H.D., Silva, MG Ramalho, J.C., 2010. Seasonal vegetative growth of different age branches of conilon coffee tree. Semina: Ciências Agrárias 31 (3), 619–626.

Partelli, F.L., Batista-Santos, P., Campos, P.S., Pais, I.P., Quartin, V.L., Vieira, H.D., Vieira, H.D., Ramalho, J.C., 2011. Characterization of the main lipid components of chloroplast membranes and cold induced changes in *Coffea* spp. Environ. Exp. Bot. 74, 194–204.

Partelli, F.L., Marré, W.B., Falqueto, A.R., Vieira, H.D., Cavatte, P.C., 2013. Seasonal vegetative growth in genotypes of *Coffea canephora*, as related to climatic factors. J. Agric. Sci. 5, 108–116.

Ramalho, A.R., Rocha, R.B., Souza, F.F., Veneziano, W., Teixeira, A.L., 2016. Progresso genético da produtividade de café beneficiado com a seleção de clones de cafeeiro' Conilon'. Revista Ciência Agronômica 47 (3), 516–523.

Ramalho, J.C., Rodrigues, A.P., Lidon, F.C., Marques, L.M.C., Leitão, E., Fortunato, A.S., Pais, I.P., Silva, M.J., Scotti-Campos, P., Lopes, A., Reboredo, F.H., Ribeiro-Barros, A., 2018. Stress cross-response of the antioxidative system promoted by superimposed drought and cold conditions in *Coffea* spp. PLoS One 13 (6), 1–30. https://doi.org/10.1371/journal.pone.0198694.

Resende, M.D.V., 2002. Genética biométrica e estatística no melhoramento de plantas perenes. Embrapa Informação Tecnológica, Brasília.

Resende, M.D.V., 2007. Selegen REML/BLUP: sistema estatístico e seleção genética computadorizada via modelos lineares mistos. Embrapa Florestas, Colombo.

Resende, M.D.V., Duarte, J.B., 2007. Precisão e controle de qualidade em experimentos de avaliação de cultivares. Pesquisa Agropecuária Tropical 37 (3), 82–194.

Rocha, R.B., Vieira, A.H., Gama, M.B., Rossi, L.M.B., 2009. Genetic evaluation of bandarra (*Schizolobium amazonicum*) provenances by the REML/BLUP methodology. Sci. For. 37 (84), 351–358.

Rodrigues, W.P., Vieira, H.D., Barbosa, D.H.S.G., Souza Filho, G.R., Candido, L.S., 2013. Adaptability and genotypic stability of *Coffea arabica* genotypes based on REML/BLUP analysis in Rio de Janeiro State, Brazil. Genet. Med. Res. 12 (3), 2391–2399.

Rodrigues, W.P., Martins, M.Q., Fortunato, A.S., Rodrigues, A.P., Semedo, J.N., Simões-Costa, M.C., Pais, I.P., Leitão, A.E., Colwell, F., Goulao, L., Máguas, C., Maia, R., Partelli, F.L., Campostrini, E., Scotti-Campos, P., Ribeiro-Barros, A.I., Lidon, F.C., Damatta, F.M., Ramalho, J.C., 2016. Long-term elevated air [CO2] strengthens photosynthetic functioning and mitigates the impact of supra-optimal temperatures in tropical *Coffea arabica* and *C. canephora* species. Glob. Change Biol. 22, 415–431. https://doi.org/10.1111/gcb.13088.

Rodrigues, H.S., Cruz, C.D., Macêdo, J.L.V., Resende, M.D.V., Lopes, R., Borém, A., 2017. Genetic variability and progeny selection of peach palm via mixed models (REML/BLUP). Acta Scientiarum 39 (2), 165–173. https://doi.org/10.4025/actasciagron.v39i2.32495.

Rosado, A.M., Rosado, T.B., Alves, A.A., Laviola, B.G., 2012. Seleção simultânea de clones de eucalipto de acordo com produtividade, estabilidade e adaptabilidade. Pesquisa Agropecuária Brasileira 47, 964–971.

Santos, A.D., Ceccon, G., Teodoro, P.E., Correa, A.M., Alvarez, R.C.F., JFDA, Silva, Alves, V.B., 2016. Adaptabilidade e estabilidade de genótipos de feijão caupi ereto via REML/BLUP e GGE Biplot. Bragantia 75 (3), 299–306.